Feeling the Beat Where it Counts: Fostering Multi-limb Rhythm Skills with the Haptic Drum Kit

Simon Holland, Anders J. Bouwer, Mathew Dalgleish, Topi M. Hurtig

Music Computing Lab
Department of Computer Science
The Open University
Milton Keynes, MK7 6AA, UK
{s.holland, m.dalgleish, a.bouwer, t.hurtig} @open.ac.uk

ABSTRACT

This paper introduces a tool known as the Haptic Drum Kit, which employs four computer-controlled vibrotactile devices, one attached to each wrist and ankle. In the applications discussed here, haptic pulses are used to guide the playing, on a drum kit, of rhythmic patterns that require multi-limb co-ordination. The immediate aim is to foster rhythm skills and multi-limb coordination. A broader aim is to systematically develop skills in recognizing, identifying, memorizing, retaining, analyzing, reproducing, and composing polyphonic rhythms. We consider the implications of three different theories for this approach: the work of the music educator Dalcroze (1865-1950 [1]; the entrainment theory of human rhythm perception and production [2,3]; and sensory motor contingency theory [4]. In this paper we report on a design study; and identify and discuss a variety of emerging design issues. The study demonstrates that beginning drummers are able to learn intricate drum patterns from haptic stimuli alone.

Keywords

Haptic Drum Kit, haptic interaction, vibrotactile, Dalcroze, drumming, multi-limb coordination, rhythm, polyphonic rhythm, guidance, instruction, entrainment, embodied cognition, sensory motor contingency, temporal patterns.

ACM Classification Keywords

H.5.2 User Interfaces: Haptic I/O; Theory and Methods; Prototyping. H.5.5. Sound and Music Computing: Methodologies and Techniques; Systems.

General Terms

Design, Theory, Human Factors, Performance, Measurement Experimentation.

INTRODUCTION

This paper explores a new tool known as the Haptic Drum Kit. While the system has potential applications for teaching and refining drumming skills, its broader aim is to

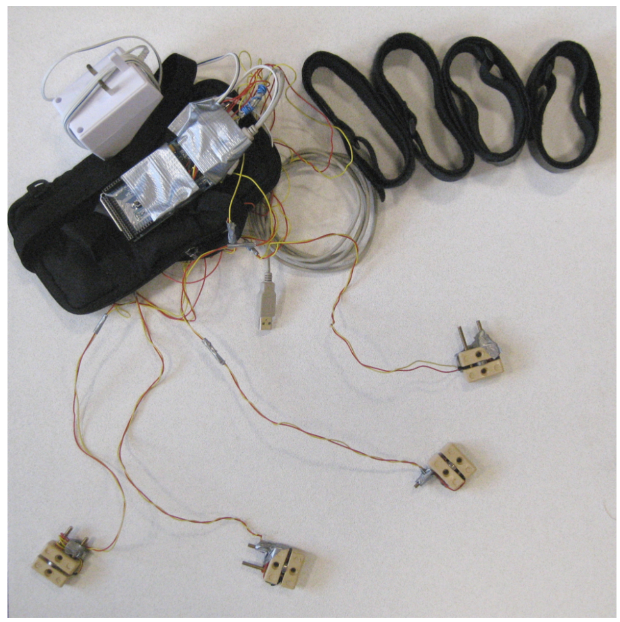

Figure 1. The Haptic Drum Kit vibrotactiles (bottom), circuit board and pouch belt (top left), cables, and elastic straps (top right).

systematically foster skills in recognizing, identifying, memorizing, retaining analyzing, reproducing and composing monophonic and polyphonic rhythms in diverse contexts, for example promoting rhythmic independence of hand for piano players and other instrumentalists [5]. There appear to be potential applications for improving the health and welfare of those with restricted mobility.

Our approach is informed by three bodies of theory: the work of the music educator Dalcroze (1865-1950) [1] and of organizations that build on his legacy; the entrainment theory of human rhythm perception and production [2]; and research in embodied cognition - in particular sensory motor contingency theory [4]. In this paper we introduce the Haptic Drum Kit, and present the theories influencing our approach, a variety of design issues, and a pilot study.

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Human innate capacity for rhythm

Humans are periodicity seekers. That is to say, we have the tendency involuntarily to notice and pay attention to periodic phenomena in the environment. This occurs irrespective of modality: visual, auditory or haptic [2]. Additionally, humans have a tendency to imitate such perceived periodicities, either vocally or through bodily motions [2]. This mimicry may be enacted either in real time, or later, on recall. These temporally focused capacities seem to be absent in other species (with some limited exceptions, for example fireflies and parrots) but are richly elaborated in all human cultures. There is evidence that humans are particularly attuned to periods in the range from about 200 milliseconds to 2 seconds [3], and may have dedicated banks of neurons for the purpose.

These capabilities appear to lie at the heart of many human activities. This is perhaps most obvious in the case of music, an activity universal across cultures [6]. However, these capacities also feature in a wide range of other human activities, including dancing, games, speech, turn-taking, child nurture, martial arts, mimesis in general and countless other behaviours.

Building on these innate capacities, systematic education and training can be applied to develop more elaborate skills in *recognizing, identifying, retaining, analyzing and reproducing* rhythms. Such training is claimed by Dalcroze and others to have socially positive outcomes, most evidently in music, but also elsewhere. For example, learning to move rhythmically plays a key role in improving mobility in conductive education [7]. There is some evidence that developing better rhythmic facility may help older people avoid falls [8].

The role of embodied physicality in rhythm training

The music educator Emil Dalcroze (1865-1950) noticed that his students seemed unable to deal with technical and written aspects of music connected with rhythm if they lacked experience of enacting and feeling those rhythms with their own bodies. Simply *hearing* examples did not appear to be sufficient. Dalcroze proposed that students had to become competent in *enacting* representative rhythms with their own bodies. Once this had been achieved, problems in dealing with technical and abstract aspects of rhythm seemed relatively easily solved. In some cases, the requirement for bodily enacting a rhythm can be relatively undemanding, for example if the rhythm is a simple pattern that can be tapped with a single finger (i.e. *monophonic*). However, more challengingly, some rhythms are *polyphoni*c, i.e. consist of more than one rhythm played in parallel, such as are generated by a group of musicians, each playing a different instrument, or by a solo pianist playing with two hands independently, or an individual drummer employing all four limbs at once. Polyphonic rhythms are generally harder to recognize, memorize, analyze and reproduce than monophonic rhythms, even though each of the individual rhythms may be simple.

Dalcroze's approach

In order to encourage competency in enacting rhythms, particularly polyphonic rhythms, Dalcroze invented a system of rhythmic 'gymnastics' or 'eurhythmics'. Amongst other things, this involved asking students to walk at a regular pace, while moving their arms in synchrony at, for example, twice or three times the rate. Dalcroze's approach, and its modern refinements, now represent established strands within rhythm education.

Skills with *polyphonic* rhythms represent interesting learnable extensions of periodicity seeking; the ability to reliably identify and generate not just individual periodic processes, but *parallel periodic processes* in general. If, for whatever reason, we wish to develop such a facility with parallel periodic processes (and this is a key aim of the Haptic Drum Kit) then it is illuminating to consider sensory motor contingency theory.

Sensory motor contingency theory

Sensory motor contingency theory [3] suggests that typically, in order to learn to organize and respond appropriately to sensory input in some new domain or context, it is an essential precursor that the individual learner's motor actions have the power to affect relationships in the domain being sensed, causing effects sensed by the individual's own sensory apparatus. In situations where this very specific kind of feedback is absent, competency has been observed to fail to develop.

This principle has been demonstrated in numerous different contexts and time scales. Notable examples include the development of the visual perception systems of neonate kittens [9]; systematic adaptation to sensory substitution in blind adults over months [10]; and opportunistic learned sensory substitution in sighted adults over minutes when carrying out simple tracking tasks [11].

Sensory motor contingency theory provides a strong principled motivation for the Haptic Drum Kit approach, as follows. Sensory motor contingency, assuming its applicability here, suggests that if learners are to develop their skills in *recognizing, identifying, memorizing, analyzing, reproducing and composing* rhythms, then their motor actions must be able to actively manipulate those rhythms at an adequately fine level of detail. But now consider the particular case of polyphonic patterns, i.e. *parallel* periodic processes. More or less the only effective way that people can reliably and intentionally physically enact parallel periodic processes rhythms is through the co-ordinated action of multiple limbs[1]. Thus, given that our

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[1] There are exceptions. One alternative is the use of multiple fingers, although fingers have less independent dynamic range, and are subject to physical limitations that hamper independent movement. Other alternative approaches to enacting polyphony are to use special tools, such as double-ended sticks, to sound different instruments,

aim is to develop facility with parallel periodic processes, developing coordinated multi-limb activity is paramount. It is for this reason that the design of the Haptic Drum Kit focuses specifically on polyphony, and on the need for the constituent rhythms to be felt directly in the appropriate limb.

Entrainment

The last of our theoretical perspectives, Entrainment, underpins a final key point in the design of the Haptic Drum Kit. Entrainment is a term, originally from physics, to describe how two or more physically connected rhythmic processes interact with each other in such a way that they adjust towards and eventually 'lock in' to a common phase or periodicity. However, the concept has been demonstrated to have rich and unexpected applications in perception, neuropsychology and music psychology [2]. While multi-limb activity appears to be a more or less necessary precursor to developing mastery of polyphonic rhythms, entrainment theory suggests that adequately trained individuals may subsequently learn to entrain polyphonic rhythms internally at will. We will return to this point when discussing design issues.

Although its theoretical implications are rich, the Haptic Drum Kit is simple in conception, construction and operation.

THE HAPTIC DRUM KIT

The Haptic Drum Kit consists of the following:

- a set of four vibrotactiles + elastic velcro bands,
- an Arduino electronic circuit board + a pouch belt,
- a midi drum kit (drums + sound module),
- a computer running Max/Msp and software for audio and midi recording and playback,
- the Haptic Drum Kit program, written in Max/Msp,
- a stereo audio system for playback.

The vibrotactiles are mounted between small plastic blocks, to protect them from damage, and with the aim of increasing resonance. Elasticated velcro straps are used to attach the vibrotactiles to each limb: two to the wrists, and two to the ankles. The vibrotactiles are connected by wires to the Arduino board that controls them. The Arduino is worn in a belt pouch. This arrangement allows a person wearing the vibrotactiles to move all four limbs independently without hindrance when seated on a drum stool. The vibrotactiles are controlled by a laptop running a program written in Max/Msp and a sequencer. In the mode of use employed in this study (other contrasting applications are possible), midi files encoding drum patterns (known as 'guide tracks') are played back by the sequencer to control the generation of haptic output, via signals that are fed to the vibrotactiles. The sequencer also controls synchronized audio output when required. Presentation can be in any of three modes: audio only; audio plus haptics; or haptics only. The sequencer running the guide track is also used to record the player's performance timing data. For convenience of recording this data, we employ a midi drum kit, though this is not an essential part of the system (see the design issues section, below). The stereo audio system is used to play back both the sound created by playing the midi drum kit, and the sound from the guide track, when required.

Characteristics of the haptic signal

In the version of the Haptic Drum Kit used in the pilot, we used inexpensive 12000 rpm rotary-motor type vibrotactile devices similar to those used in wiimotes. To make these devices feel as haptically 'loud' as possible, we used a full amplitude voltage pulse for the device – although the resultant haptic effect was still not quite as 'loud' as we would have preferred. We found that we had to deliver this pulse for a minimum of about 50 ms for the haptic signal to be clearly felt. In order for two signals to be felt as distinct rather than merging into one, we found that we had to leave a minimum gap of about 50 ms. When a pulse is applied, the motor rapidly accelerates to a maximum speed that depends on the applied amplitude, so that the frequency of the vibration is amplitude dependent.

This pilot version of the vibrotactile drivers for the Haptic Drum Kit appeared to have three weaknesses for our purposes, which we will discuss in detail in the design issues section.

DESIGN STUDY FOR THE HAPTIC DRUM KIT

Setup

A design study was carried out with subjects learning to play drum patterns of varying complexity, with guidance of what to play presented in audio, haptics, or both.

Participants

Five participants took part in the study. Four were beginners at playing the drums; one had five years of experience drumming in rock bands and taking drumming lessons. All participants were male, and aged from late twenties to about late forties. Participants were videotaped from three different angles, and their performance on the drum kit was recorded in synchrony with the reference guide track.

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or to use the mouth and vocal chords to voice different timbres ("beatboxing"). Such approaches are problematic for our purposes, because they are difficult to master, especially when a pattern demands that instruments sound simultaneously. Another partial alternative is to collaborate with others – valuable in its own right, but not a way of enacting parallel processes with one's own body.

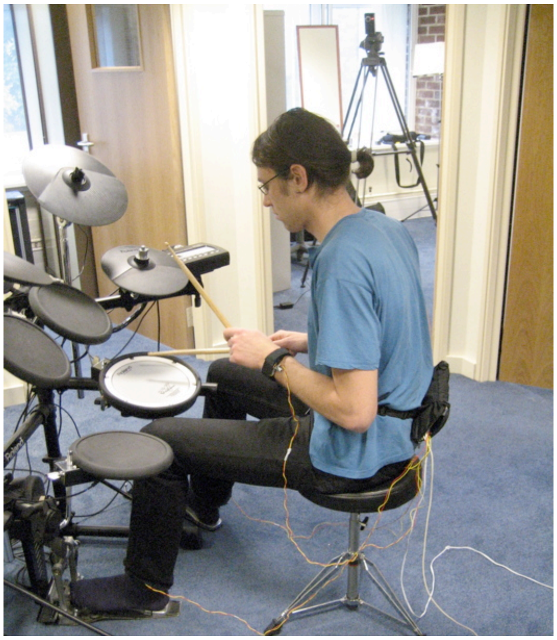

Figure 2. The Haptic Drum Kit in use.

Selection of reference rhythms

Twenty reference rhythms to be learned were drawn from four broadly representative technical categories as follows. The rhythms included patterns for two, three and four limbs. The categories were as follows (see the figure legends for further explanation).

- Metrical rhythms, 8 beat and 16 beat.
- Figural rhythms, involving syncopation, based on the Cuban clave.
- Simple regular beats rendered figural by the way events are distributed across limbs, thus subtly varying tone colour – e.g. the alternation of single and double strokes in the paradiddle.
- Polyrhythms, e.g. 2 vs 3, 3 vs 4, 2 vs 5, 4 vs 5.

Taking representative rhythms from these categories was motivated by evidence from music psychology that the human perception system deals with purely metrical and figural material in different ways [12,13]. Equally, there are contrasts between hierarchical metre and polyrhythm [14,15]. Patterns such as the paradiddle are regular in terms of their onset times but complex in their emphasis patterns. Choices from these varied categories were deemed a precaution against over-generalisation of any findings on the basis of an overly narrow class of rhythms.

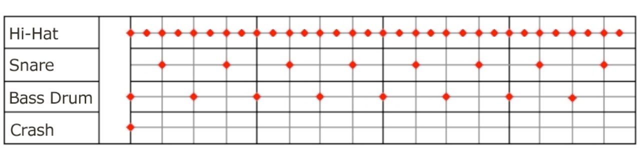

Figure 3. A metrical rhythm.

Metrical rhythms can sound rich, but they are simple regular grids built from hierarchically layered temporal streams. Each limb typically plays a completely regular beat, whose period is a low prime multiple of (and whose events always co-incide with events from) the adjacent faster layer. An exception in this example is that, following rock conventions, the snare is phase shifted by 180 degrees. Metrical rhythms are common in western music.

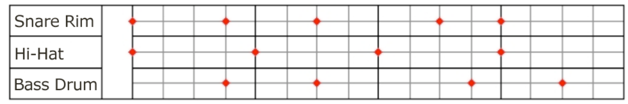

Figure 4. A Cuban clave rhythm.

In a predominantly figural rhythm, like this Cuban clave, the patterns played by a given limb are irregular. This kind of organization, especially when polyphonic (multi-limbed), as in this example, tends to make more challenging demands on memorization, analysis, retention and reproduction than purely metrical patterns.

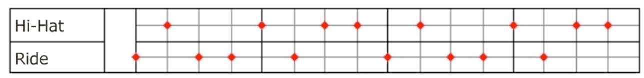

Figure 5. A paradiddle.

Viewed globally, a paradiddle is just a regular uniform beat, consisting of a continuous stream of notes assigned to two different limbs. However, viewed from the perspective of each individual limb, it requires a complex figural pattern to be played, involving single and double strokes and different time intervals. When played on one drum, the alternation of single and double strokes results in subtle variation in emphasis and tone color. In the exercise, the pattern was distributed over ride and hi-hat, to make it easier to discern what the individual limbs should play.

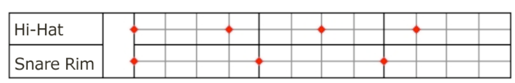

Figure 6 A two-handed polyrhythm: 3 against 4.

Note that while polyrhythms are necessarily polyphonic (a term explained earlier), polyrhythms occupy a somewhat exotic subset. Like metrical rhythms, polyrhythms are built from completely regular layered elements. However, *unlike* metrical rhythms, polyrhythms are *not* hierarchical. That is to say, the periods in slower layers need not coincide with beats in faster layers (because the periods are relatively prime) except at the beginning of complete cycles. Polyrhythms are typically found in non-western musics.

Experimental Tasks

The experimental tasks were designed to focus on multi-limb coordination in different kinds of drum beat patterns.

After a short introduction about the Haptic Drum Kit and the experimental setup, each participant was given a chance to adjust the drum kit so that each drum could be hit comfortably, and warm up by playing some single strokes and double strokes. Then, the patterns were presented, and participants were asked to play along with the pattern as well as they could. There were twenty patterns chosen from the categories noted above. Patterns were presented at varied tempi. For half of the novice participants, the order of the audio and haptics conditions was reversed, to balance the effect of ordering over the participants. Subjects were observed while playing. Afterwards, a structured interview took place to explore each participant's views.

Figure 7. Close up of vibrotactiles attached to ankles and wrists.

RESULTS

We will focus specifically on those results that illuminate design issues.

In terms of broad attitudes, all subjects expressed an interest in using the haptic system again, and most found the system comfortable to wear. However, all found the audio clearer to attend to than the haptic presentation, and all found it easier to play in time with the audio presentation than the haptic presentation. Of the three forms of presentation (audio only; haptic only; and audio plus haptic), all preferred audio plus haptic.

General attitudes to haptic presentation

There was a range of generally (but not exclusively) positive comments on the haptic presentation. One user commented that the haptic guidance was "intimate", promoting "a focus inside yourself". Comments included "it's like the rhythm is already there" and "when you hit the right rhythm, the haptics feel nice". It was commented that a particularly positive feature of the haptics, as compared to audio, was that you already knew what each limb had to do, instead of having to work out the division of labour. One subject commented that the haptics were extremely useful for validating the audio. The fittingness of the common phrases "feel the rhythm" and "feel the beat" was noted by more than one participant.

'Quietness' of the Haptics

It was commented that the haptic 'volume' of the haptics was not high enough. One subject complained that this was particularly true for the ankles/feet – the vibrotactiles on the feet seemed subjectively 'quieter' than on the wrists. A related effect of the level of the haptics, noted by more than one subject was that when one started playing, the impact of striking the drums had a tendency to drown out the signal from the vibrotactiles (haptic masking). For the purposes of studying some complex rhythms, some subjects wished they could selectively amplify, select or silence the four haptic channels individually.

Blurred haptic onset

Several subject commented that, particularly with fast rhythms, the buzzers had a somewhat blurred attack. Another subject commented that in the case of fast sequences, one pulse could seem to blur into another, saying "when lots of notes are presented, it is difficult".

Lack of relative emphasis of haptic pulses

Some subjects commented that, in the case of looping patterns, it was hard to know where the pattern should be started for purposes of memorisation, as all of the haptic pulses had the same emphasis.

Observed 'vertical' vs. parallel behaviour

More than one observer noted the following behaviour, though given the small sample, it may not have been representative. In the audio-only presentation of complex rhythms, beginners could typically be seen learning the patterns by expanding them 'vertically'. That is to say, subjects would learn one 'line' at a time (i.e. the desired pattern for a single limb, only then moving on to the next limb). By contrast, in the haptic-only condition, beginners could several times be seen to attend silently to the haptic pulses, and then start to play a pattern combining two or more limbs simultaneously.

Individual differences

Although all subjects preferred haptic plus audio as a presentation style, there was considerable individual variation in attitude to haptic-only presentation. One subject commented that the vibrotactiles became a little annoying after a time. One noted that the vibrotactiles were a little (acoustically) noisy. One subject commented, "with only the haptics, it's really difficult".

General attitudes to audio presentation

In the case of audio-only presentation, one subject commented "you can hear how its supposed to sound" and "it's easier to parse". Negative comments included the observation that the sounds of the drum kit in the audio guide were a bit different from the sound of the drum kit, so that it was not clear what instrument to play and what limb to use. One subject noted that with the audio presentation, one had to "do one hand at a time … it's hard to memorize".

Mapping limbs to instruments

Audio recordings don't tell players which limb to play when. One subject noted that, in the case of audio presentation, one had to first listen to identify the drum associated with a rhythmic layer of interest, then find that drum on the kit, then choose a limb to play it, whereas in the case of the haptics, one knew which limb to use for each layer straight away. However, some limbs may be free to play more than one drum, so that although the Haptic Drum Kit may determine the limb, it does not necessarily determine which drum to play.

In a system designed specifically to train drummers, this issue is very important, whereas in a system designed to promote more general facility with rhythm, it is less germane. Still, it is generally useful to map instructions about different limbs to a medium that connects to specific limbs.

DESIGN ISSUES EMERGING FROM THE STUDY

Since, as already noted, the primary purpose of this paper is to illuminate design issues, we will now turn to consider design issues illuminated by the above results.

Design for entrainment vs. stimulus response

The comment that "when you hit the right rhythm, the haptics feel nice" helps to identify a vital distinction in possible designs aim. The aim of our design is crucially *not* to orchestrate stimulus response – it is to foster entrainment. To see why this must be the case, consider the following. A latency period is involved in responding to any stimulus, so that by the time the latency period has elapsed, any 'response' would be de-synchronized from the 'stimulus'. Of course, in the present mode of operation, the 'stimulus' is a recorded sequence of haptic signals, which could in principle be advanced until the 'response' was in time with audio playback. However, leaving aside issues of variation in response time (both inter- and intra-individual) any such 'response' would not then be synchronized with the stimulus – destroying the rhythm under consideration.

By contrast, the Haptic Drum Kit explicitly takes advantage of the fact that rhythmic patterns are typically highly repetitive, so that subjects can attend to a polyphonic haptic signal while internally entraining (often without playing) and then, when ready, start to reproduce the pattern in time with the continuing guide track. All of the patterns then coincide, enabling valuable entrainment. However, the observation that the impact of striking the drums could sometimes drown out the signal from the vibrotactiles seems to have hindered, at least in some cases, this useful affordance for entrainment. This leads us to the next design issue.

Upgrading the technology - onset clarity, volume, temporal resolution, and variable emphasis

The vibrotactile technology that we used in the pilot had four principal limitations that seemed to impact the user experience. In particular, the timing of onsets was spread over 50 milliseconds; pulses in sequences separated by less than about 100 ms seemed to blur into each other; the haptic 'volume' was not 'loud' enough; and since, in order to compensate, pulses were already delivered as 'loudly' as possible, it was impossible to give pulses variable emphasis, e.g. to mark the start of looped phrases. Each of these shortcomings directly translated into weaknesses noted by users. By moving to a different, better adapted vibrotactile technology in the next version of the Haptic Drum Kit, we hope to address the bulk of these issues (see the section on Further Work).

Personal flexibility - Haptic mixers: volume, balance, soloing and muting

Some subjects noted that they found it harder to feel pulses delivered to the ankles, for example, than to the wrists, and at times wished to attend to one or more individual limbs. These observations can be directly translated into design improvements. A facility is required to be able to selectively balance, mute, or isolate haptic playback to one or more limbs. It would be valuable to have such controls for the limbs available on a haptic 'mixer' with a convenient user interface for users to adjust as they wished.

In fact, the signals could already be turned on or off individually by the experimenters in the study via the Max patch, but we would like to give participants control over this feature, perhaps by adding a small control connected to the vibrotactiles on their limbs.

Drums vs. body percussion

Paradoxically, drums are inessential to the Haptic Drum Kit. Of course, drums are very valuable when using the system specifically for drumming instruction, but when the aim is more generally to develop facility in entraining polyphonic rhythms, it may be just as useful to attend to haptic guidance while striking one's own thighs or other body parts, and using one's feet to strike the ground. Indeed, body percussion is much in the spirit of Dalcroze, is readily performed in the absence of percussion instruments, and is strongly recommend by some piano teachers for promoting limb independence [5].

RELATED WORK

There is much related research, although, to the best of our knowledge, none that shares our particular focus on polyphonic rhythm and multi-limb haptic guidance.

Grindlay [16] experimented with rhythmic stimuli on the isolated single hand of beginners as training (the system physically moved the participant's hand to play the rhythm). Haptics were shown to help significantly to improve performance of playing rhythmic patterns with one hand. Haptic plus audio worked best.

Huang et al [17] built a system using a wireless haptic glove with vibrotactile effectors for each finger and investigated whether users wearing the glove improved their performance at playing simple piano tunes after passive exposure to combined audio and haptic playback, while focused on another task.

There are numerous systems which incorporate haptic feedback into virtual or physical musical instruments (rather than directing feedback to individual limbs). Examples can be found in O'Modhrain [18], Collicutt et al [19], Sinclair [20] Miranda and Wanderley [21].

There are systems which use interpersonal haptic feedback so people can feel what other players are doing, for example Kanebako and Sekiguchi [22] and Carlile and Hartmann [23].

Other systems aim to improve rhythmic performance using visual feedback e.g. Sadakata et al [24] and Timmers et al. [25]. Sadakata developed a visual feedback system for rhythm performance and in a longitudinal study showed that participants significantly benefited from long-term use over three weeks.

Spelmezan et al [26] have developed a system for tactile motion instruction for physical activities which has been applied to snowboarding.

The Hapkit [27] and the Haptic Drum [28] are interesting systems with similar names to ours, but they have essentially nothing in common with it. The former is virtual drum with force-feedback, while the latter is a physical drum that actively rebounds against single drum strikes to turn them into drum rolls.

LIMITATIONS

The aim of the investigation was a design study, rather than a formal evaluation. Some quotes were recreated from notes. Four subjects were beginners, and one was an expert: there are likely to be large beginner-expert differences, as well as individual differences. All of the subjects came from cultures with a western musical tradition. There may be large cross-cultural effects in rhythmic skills when drawing on more diverse backgrounds. Indeed, knowledge of such differences appears to have originally inspired Dalcroze [1]. Some anticipated effects of interest were hard to study due to limitations in the vibrotactiles used.

FURTHER WORK

Based on our findings, in the subsequent design iteration following this work, we are using Tactors (solenoids specifically designed for haptics) instead of vibrotactiles. These devices give cleaner, more precise signals, with a wider haptic dynamic range and finer temporal resolution. It is plausible that this will address many of the usability issues identified in the study. For example, this technology will allow signals with different degrees of emphasis, helpful in grouping rhythms and marking boundaries. These devices are currently expensive, but as haptics become more widely used, they are likely to become cheaper.

Currently our haptic guide tracks are programmed manually, or in some cases taken from commercial midi files. However, there are possibilities for beat extraction from audio files, giving the approach wider applications.

Inspired by Huang et al. [17] we plan to establish whether our *Haptic Ipod*, that replays four–limb haptic guidance on rhythms in synchrony with audio playback can produce passive learning effects while the user performs unrelated tasks, even without conscious attention being paid to the rhythms.

A Haptic drum kit designed explicitly to train drummers will have slightly different requirements from a system designed to develop entrainment skills more generally. These differences should be explored more fully.

In the current study, an important distinction is that the system gives haptic guidance, not haptic feedback. However, current technology also allows real-time feedback of measurable aspects of the actual drumming performance. For example, Timmers et al. [25] developed a system that could categorize a beginning drummer's performance as resembling an expert drummer's example of drumming on the beat, laid-back, or rushed. They used visual feedback in the form of shapes to represent these styles, or something in between. Students performed more accurately with than without the visual feedback. For our purposes, when considering expert drummers, the difference between a successful groove and an unsuccessful groove can depend simply on the phase of one limb relative to the others [29]. The Haptic Drum Kit (using solenoids) appears well adapted to communicating the need to advance or delay the beat of an appropriate single limb fractionally, to guide expert performance.

An interesting comparison point for a future study might be Dance Dance Revolution, a music video game produced by Konami, which judges how accurately players' foot impacts track musical and visual cues.

Drummers in live performances sometimes need to keep in time with recorded elements of a performance. This can be confusing under high sound levels, and is often managed by means of an audio 'click track'. A *haptic click track* – (particularly a *hierarchical* haptic click track, able to communicate an entire metrical structure) might perform this role better in situations with high sound levels, without getting in the way of other audio elements.

Haptic click tracks could also have applications as scaffolding for improvising drummers, and for guiding ensembles to start in synchrony.

CONCLUSIONS

This paper has introduced the Haptic Drum Kit, and put it in the context of three relevant theories: Dalcroze [1] Entrainment [2]; and sensory motor contingency [4]. We have reported on a design study and identified a variety of design issues emerging from the study. The results indicate that beginning drummers are able to learn intricate drum patterns from the haptic stimuli alone, although haptic plus audio is the mode of presentation preferred by subjects. Diverse possibilities for further work stemming from this research have been identified.

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